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COSMIC RADIATION

Peter Meyer

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Presented at the IGY/IGC Symposium
~~University of California,~~ Los Angeles, August 1963

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Forbush's discovery that the intensity of cosmic radiation which reaches the earth is correlated with the general level of solar activity has stimulated an extensive program of research aimed at the description of the mechanisms by which the sun is capable of influencing the flux of galactic cosmic ray particles into the inner solar system. Today we still are in the middle of these investigations. Indeed, this type of research ties the field of cosmic radiation to the activities of the International Geophysical Year which lies behind us, and the International Year of the Quiet Sun which is ahead of us.

Both these enterprises include in their aims the exploration of the physical phenomena in interplanetary space, phenomena which are controlled by the outflux of energy from the sun. This energy is essentially emitted in two forms: Electromagnetic radiation and particle radiation. It is the latter which interests us in connection with the galactic cosmic radiation. Rapid theoretical as well as experimental developments have taken place in this field during the past years which drastically changed the point of view taken prior to the IGY. I shall not restrict myself to a review of the studies during IGY, but rather try for a limited part of the cosmic ray research to develop the position into which the work which was done before, during and after the IGY has placed us now, and where we may expect to go from here. I can avoid talking in detail about the evidence for the solar plasma flux and the consequences which this flux has for the configuration of magnetic fields and particles in the solar system, since this topic has been covered by Dr. Parker.

Looking back from today's point of view, it appears to be surprising that the solar influence on cosmic radiation was not discovered much earlier in the course of cosmic ray research. The reason can be found in the fact that the solar modulation effects are large only in the low energy portion of the primary cosmic ray spectrum and that we have only in the past decade learned to extensively study the low energy primary cosmic rays. In this region, however, the cosmic ray particles are a powerful tool to investigate the configuration of magnetic fields and their changes in the solar system. In fact, experiments on the variations of intensity and energy spectrum of the cosmic radiation have greatly contributed to the formulation of the concept of a "solar wind", a concept which only afterwards could be tested and confirmed through direct experiments.

Fig. 1 has been taken from the original paper by Forbush[1], which clearly showed for the first time the anticorrelation between solar activity -- here represented by the sunspot number -- and the intensity of cosmic radiation. Forbush's paper was published in 1954, two years before the IGY. When the International Geophysical Year got under way, the link between solar activity and cosmic radiation was fully recognized.

Through the balloon experiments by Neher[2] and his coworkers and the airplane experiments of Meyer and Simpson[3], the strong energy-dependence of the solar modulation became evident. Fig. 2 shows some of the results of Neher with balloon-borne ion chambers, displaying the dramatic changes which take place at extremely low primary particle energies between years of high and low solar activity.

The changes in the energy spectrum at higher energies could be demonstrated by flying a neutron monitor at aircraft altitude along identical trajectories of almost constant geomagnetic longitude and in this way using the geomagnetic field as an energy spectrometer.[3] Fig. 3 is a reminder of the results obtained in this experiment which also was, as Neher's experiment, carried into the IGY period. One can see how the slope of the intensity versus latitude curve as well as the position of the "knee" change with the level of solar activity.

It is a result of the strong energy dependence of the solar modulation mechanism that the eleven-year intensity variation is much more readily displayed in cosmic ray neutron monitors that respond predominantly to the low energy portion of the primary radiation. Hence, the barely detectable effect first noticed by Forbush with the use of ion chambers becomes very large in neutron monitors. Fig. 4 shows the time dependence of the neutron monitor intensity for the past ten years taken at the Climax station by Simpson.

The experiment which most clearly shows the behavior of the low energy portion of the primary proton spectrum as a function of the solar cycle was carried out by McDonald[4], and McDonald and Webber[5]. McDonald had introduced the method of simultaneously observing the energy loss of a particle and the light output produced in a Cerenkov radiator. Through the measurement of these two parameters he was able to determine the charge and the energy of individual particles over a certain energy range.

A result of this work is shown in Fig. 5. One clearly sees the deviation of the primary spectrum from a power law towards lower energies which is interpreted as a suppression of galactic particles from the vicinity of the earth. The intensity, after going through a peak, decreases rapidly with decreasing energy. The peak would roughly correspond to the "knee" observed in the latitude curves. It is important to note the behavior of the primary α-particles, particularly the similarity of the rigidity spectrum and the similarity of the magnitude of the intensity variation of corresponding proton and α-particle rigidities. A number of experiments, notably those of Freier, Ney and Fowler;[6] Freier, Ney and Waddington,[7] and of Fichtel,[8] confirm that, in similar rigidity intervals, α-particles are modulated by the same amount as protons.

More recently, experiments made at higher geomagnetic latitude and with instrumentation suitable to specifically study the low energy particles were made by Vogt[9] and Meyer and Vogt[10]. They exhibited a relatively large flux of protons at low energy near solar maximum which we now interpret as being of solar origin.

Data on heavier primary particles are much more scarce. They indicate however that the rigidity spectrum is modulated in the same fashion as that of the primary protons and α-particles throughout the eleven-year cycle. The available data on medium and heavy nuclei have been compiled by Webber[11] in a summary article. This compilation is shown in Fig. 6, where the particle flux is compared with the neutron monitor rate of the Mt. Washington station. The data are consistent with the assumption that the medium and heavy primaries are subjected to the same modulation as the protons and α-particles. This similarity in the behavior of particles with quite different charge and different e/m points strongly toward a rigidity dependent modulation mechanism.

This discussion has been restricted to the long-term variations of cosmic rays. There exists a number of short term variations whose amplitude, characteristics and frequency of occurrence is controlled by solar activity. In most cases these events can be identified with individual phenomena on the sun. I shall only briefly discuss the short term fluctuations, most of which are less understood than the eleven-year solar cycle variation. The most outstanding of these phenomena is the Forbush type decrease, characterized by a sudden drop in cosmic ray intensity which slowly recovers in periods of days or weeks. Its occurrence is closely correlated with solar flares. The Forbush decrease follows a flare by one to two days. It is clearly a modulation effect which influences the various components of the primary radiation. Simultaneous observations of protons and α -particles show a complete correlation in corresponding rigidity intervals. Fig. 7 shows a comparison between the total cosmic ray flux as observed by a neutron monitor and the α -particle flux measured at balloon altitude during a number of Forbush decreases.[12] In Fig. 8 this correlation is shown by plotting the α -particle flux versus the monitor intensity. On July 18, 1959, the lowest particle intensity ever observed was measured.

The rigidity dependence of the Forbush decrease has been investigated by several authors. The results are not clear-cut and there may or may not be a different dependence than that found for the eleven-year radiation.

I shall here not discuss the observations on daily variations but rather refer to the recent work by Dessler, Ahluwalia and Gottlieb[13] and their interpretation. The 27 day recurring intensity variations have so far contributed least to our understanding of the solar controlled modulation phenomena.

Dr. Parker, in a preceding paper has outlined the ideas that led to the recognition of the existence of a solar wind. He has discussed the implications of the solar wind on the motion of energetic particles. There is no doubt today -- in spite of some alternative details in the models --that the solar wind is the agent responsible for the changes in intensity and energy spectrum which we observe in the cosmic radiation. I can concentrate here on the experimental results which test the solar wind model. The most important tests came about through the availability of space probes which carried cosmic ray instrumentation to large distances from the earth. The experiments on board Pioneer V were the first to establish the fact that the eleven-year modulation as well as the Forbush decrease are phenomena which are not localized near the earth or its immediate environment, but rather affect large volumes of the inner solar system. Pioneer V carried cosmic ray detectors from the University of Chicago[14] and the University of Minnesota.[15] A triple coincidence proportional counter telescope measured protons with energy in excess of 75 MeV. An ion chamber and a Geiger counter observed the total particle flux and ionization separately. This vehicle was launched March 11, 1960 and moved along a trajectory approaching the orbit of Venus. Data were received for about two months. During that period Pioneer V approached the sun by 0.1 a.u. A study of the cosmic ray flux as a function of distance from the earth revealed that the volume of space affected by the decrease in primary particle intensity in the years of solar activity maximum --and 1960 is only one to two years after the maximum --is not restricted to the vicinity of the earth, ruling out any modulation mechanisms which invoke the presence of the earth. It shows in addition that this volume must have linear dimensions at least of the diameter of the orbit of Earth, since we do not observe any seasonal changes of cosmic ray intensity. The second important result is the evidence that the cosmic ray intensity stays constant over a radial solar distance from 0.9 a.u. to 1 a.u. This means that the modulating "barrier" is located outside of the orbit of the earth. Fig. 9 is taken from a paper by Fan, Meyer and Simpson[14] displaying the cosmic ray intensity as a function of distance from the earth. Similar conclusions can be reached from the results of Arnoldy, Hoffman and Winckler[15] who provided the ion chamber and Geiger counter on Pioneer V. These findings have more recently been confirmed and substantiated by ionization chamber and counter measurements on Mariner II.[16] Although the observations on Mariner II were made in 1962 in the declining phase of solar activity, the low energy cosmic ray flux in the vicinity of the earth was still decreased by a factor of about 2 below the value of solar minimum. A change in intensity as a function of solar distance would therefore have to be observable if the modulation "barrier" were located partly within the earth's orbit. Mariner II was able to transmit data until the point of encounter with Venus. No change in the average intensity was noted between 1 and about 0.7 a.u. radial distance from the sun.

While discussing the results that were obtained on the two deep space probes, I may come back for a moment to the phenomenon of the Forbush type decrease. At the time at which Pioneer V had a distance of about 5 million miles from the earth, high latitude neutron monitor stations recorded a Forbush decrease of about 20%. An intensity decrease of 30% was simultaneously observed by the cosmic ray detectors on Pioneer V. Taking into account the difference in the low energy response of the neutron station and the space probe instruments, one finds that the Forbush decrease occurred with full amplitude in a region far removed from the earth. This observation, therefore, establishes the fact that the mechanism responsible for the Forbush decrease also operates over a large volume and is not restricted to the vicinity of the earth. The presence of the earth and its magnetosphere is unnecessary for the production of these decreases.[17]

The developments which have been discussed took place in the last ten years, before, during and after the IGY. In this short period of time most of the current ideas concerning the solar controlled phenomena in interplanetary space which influence the cosmic radiation were formed. About two years from now we shall reach the next minimum of solar activity and we shall approach this period with firstly, a new understanding of interplanetary physics, and secondly, with greatly advanced experimental techniques in our hands. Both these conditions should make IQSY a unique enterprise.

Before discussing some directions of cosmic ray research which are of particular interest during the quiet sun period, I summarize again a few of the facts which emerged from the work of the past years.

The eleven-year modulation of cosmic ray intensity shows a strong rigidity dependence. Higher amplitudes are observed at progressively lower rigidities. Protons and heavier nuclear species of the same rigidity exhibit the same modulation. This indicates that the mechanism responsible for the modulation is rigidity dependent. There exists today direct experimental evidence for the presence of interplanetary magnetic fields and there is little doubt that these fields are the agent producing the eleven-year modulation. The configuration of the magnetic fields is controlled by the flux of plasma from the sun. The strength of this "solar wind" has been calculated by Parker[18] on the basis of cosmic ray observations, geomagnetic evidence and the known properties of the solar corona. Its existence is now established through direct experiments.[19] Measurements on space probes have shown that the volume affected by the eleven-year modulation has linear dimensions larger than the orbit of earth. Within that volume the intensity appears to be constant and reduced below the galactic cosmic ray level throughout most of the solar cycle. It is not yet known at what distance from the sun the modulating region is located; its thickness and field configuration are dso unknown. There exist, however, theoretical ideas as to the nature and origin of the modulating region. Some interesting evidence was recently obtained by Simpson[20] which bears on this question. Forbush[21] and Neher[2] have pointed out that there exists a time lag between the average sunspot number and the intensity of cosmic rays as a function of time. Using the University of Chicago neutron monitor network, Simpson studied this question in more detail, showing first that the level of solar radio emission and geomagnetic activity are correlated without phase shift with the average sunspot number. One may infer, therefore, that the strength of the solar wind is also in phase with the sunspot number. Simpson then shows that the cosmic ray intensity is not a simple and unique function of sunspot number, but is quite different for the same level of solar activity at the inclining and the declining portion of the cycle, exhibiting the phase shift discussed by Forbush and by Neher. The nature of this dependence, however, varies with the energy of the primary cosmic ray particles. In Fig. 10, the cosmic ray intensity is plotted against the average sunspot number for various cut-off energies. The large difference in cosmic ray intensity for similar sunspot numbers in the increasing and declining phase of the solar cycle can be clearly seen. The figure also shows that one it probably not dealing with a simple phase shift but rather a relaxation phenomenon. It is likely that this behavior reflects the change in scale size of the scattering centers involved in the modulation throughout the solar cycle.

In the past few years several new discoveries have been made which lead to experiments of importance for IQSY. Balloon experiments carried out by Vogt[9] and Meyer and Vogt[10] at high geomagnetic latitude gave details of the primary proton spectrum in the energy region from 70 to 350 MeV. It was found that even in years of enhanced solar activity there exists a considerable flux of protons in this energy region, which should be absent if our ideas on the modulation mechanism are correct. The presence of these low energy particles was confirmed by nuclear emulsion studies[22] and through satellite observations.[23] There is still some discrepancy among various experimenters as to the exact flux and shape of the energy spectrum, but the presence of these particles appears to be established. More recent results indicate that these protons are of solar origin during the solar active years. From 1962, on, we begin to see, however, the influx of low energy galactic protons which show an energy spectrum quite different from the solar protons which were observed earlier. We expect this flux to increase considerably from 1963 to 1965. There is little doubt that the galactic low energy protons, whose flux now appears to increase as a function of time, are identical with the particles observed by Neher in his measurements with ion chambers. In the coming years these measurements will be further pursued with the hope to gain more complete information of the primary proton spectrum in the period of solar minimum. It would be of considerable interest to find out how much residual modulation persists during minimum solar activity. Experiments are being prepared on various highly eccentric satellites which will yield a knowledge of the primary spectrum to much lower energies than those obtainable by balloon work. These experiments will, in addition, supply the energy spectra of heavier primary particles. It should, then, for the first time be possible to clearly distinguish between a rigidity and energy dependent modulation mechanism since only at very low energies are the momentum and energy not proportional to each other.

It is possible that the modulating region, if it is present at all during solar minimum, will move closer to the sun. If that were the case, experiments carried on deep space probes in the solar and antisolar directions should show a radial dependence in intensity which was absent while the sun is active. Simultaneous measurements at various solar distances of the energy spectra of protons and heavier nuclear species would shed light on the scale size of the magnetic scattering centers which are involved in the modulation.

Lastly, a word about the electron component of the primary cosmic radiation which was discovered two years ago by Earl[24] and Meyer and Vogt[25] in balloon experiments. Through these experiments we have learned that the flux of primary electrons is a few percent of the proton flux and that its energy lies between a hundred MeV and perhaps 2 BeV. We have as yet no clear evidence of their origin. It is likely that they originate in the galaxy and are the particles responsible for the production of the galactic radio noise through synchrotron radiation. If this were the case, they would be affected by the eleven-year solar modulation in a similar manner as protons of corresponding rigidity. The forthcoming years of solar minimum, when modulation is least effective, will give an opportunity to measure the energy spectrum and other properties of this component with the least modification by solar modulation. The knowledge of the galactic electron spectrum is of importance since it would yield --if combined with the radio-astronomical data --a measurement of the average strength of galactic magnetic fields.

A further important question is the ratio of electrons and positrons in the primary electron component. A measurement of this ratio will tell us whether proton - proton collisions in the galaxy are the origin of the electrons or whether ambient electrons have been accelerated to cosmic ray energies. It is one of the few experiments which promises to give direct information on accelerating mechanisms.

Both types of experiment, the measurement of the energy spectrum, and the measurement of the electron-positron ratio are presently under way and will be continued through solar minimum.

A large number of problems in the field of particle astronomy has been clarified in the IGY and post-IGY years and, as is the usual situation, an equally large or even larger number of problems has appeared as a consequence of intensive research. With the modern research tools now at our disposal, lower and lower energy particles will be investigated. This will make it possible to study phenomena of much smaller scale size and eventually to investigate the solar "weather".

It should be pointed out that this discussion has been restricted to a selected number of topics of cosmic ray research related to solar and interplanetary physics. A great deal of other important work has been carried out which I was unable to mention or to quote within the framework of this brief review.

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Figure Captions

Fig. 1 Cosmic ray intensity from 1937 to 1951 as measured by four ionization chamber stations (Forbush 1954)[1]

Fig. 2 Altitude dependence of the total ionization produced by cosmic rays measured in Thube from 1954 to 1960 (Neher 1962)[2]

Fig. 3 The nucleonic component latitude curves for 1948, 1954 and 1956 arbitrarily normalized at latitudes $> 58^{\circ}$N in order to display the magnitude of the shifts in the low-rigidity cut-off of the cosmic ray spectrum (Meyer and Simpson, 1957)[3]

Fig. 4 The monthly average cosmic ray intensity measured by the Climax neutron monitor between 1953 and 1963. (Simpson, unpublished)

Fig. 5 The primary proton and α -particle rigidity spectrum between 1955 and 1958 (McDonald and Webber, 1959)[5]

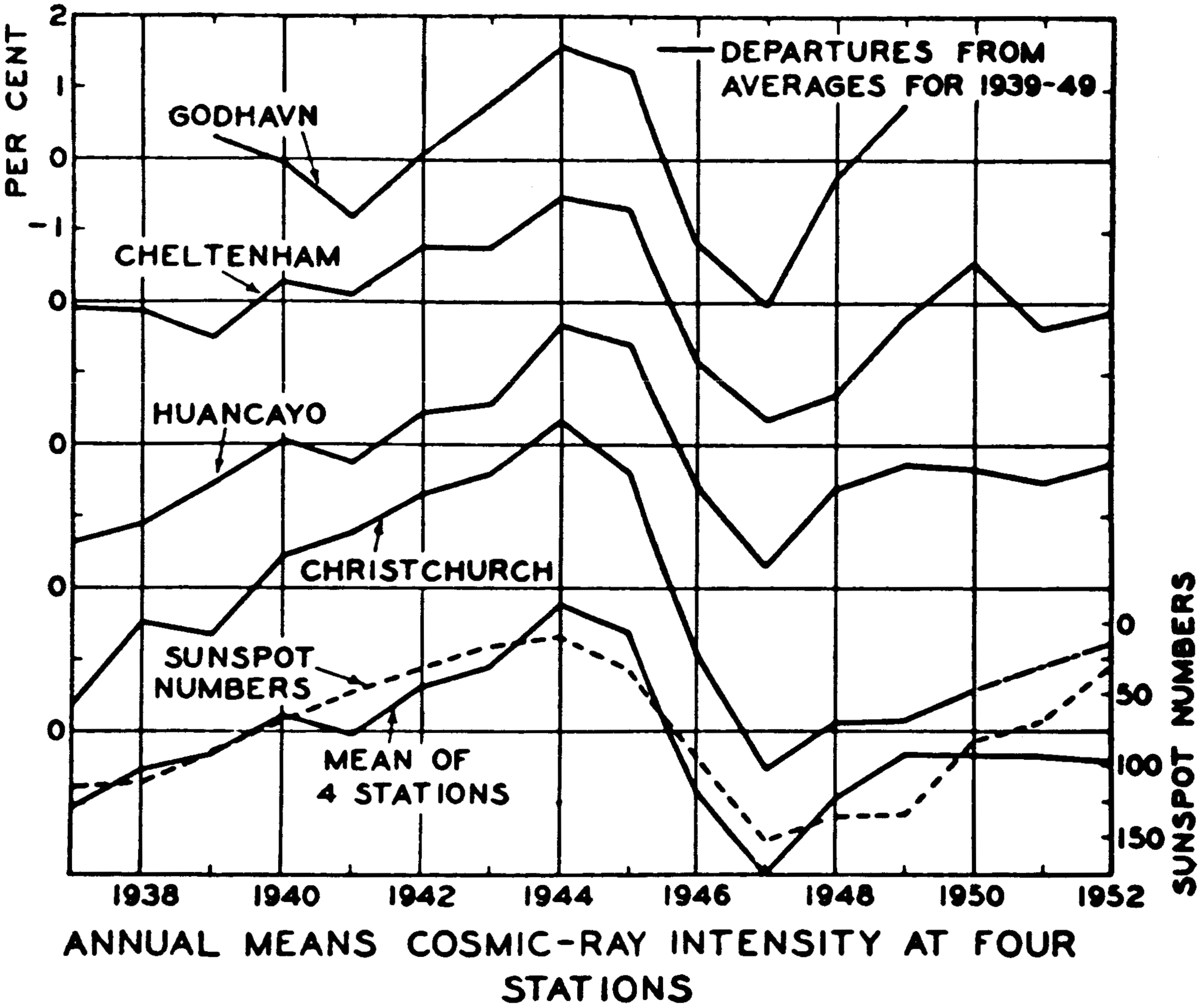
Fig. 6 Integral intensity of medium and heavy primary cosmic ray nuclei compared with the intensity of the Mt. Washington neutron monitor (Webber, 1962)[11]

Fig. 7 The cosmic ray α -particle flux ($E > 530$ MeV/nucleon) under 13.5 g/cm^2 of residual atmosphere and the nucleonic component intensity (Climax neutron monitor) during Forbush-type decreases (F) (Meyer, 1960)[12]

Fig. 8 The cosmic ray α -particle flux ($E > 530$ MeV/nucleon)vs. the Climax neutron monitor intensity from 1957 through 1959 (Meyer, 1960)[12]

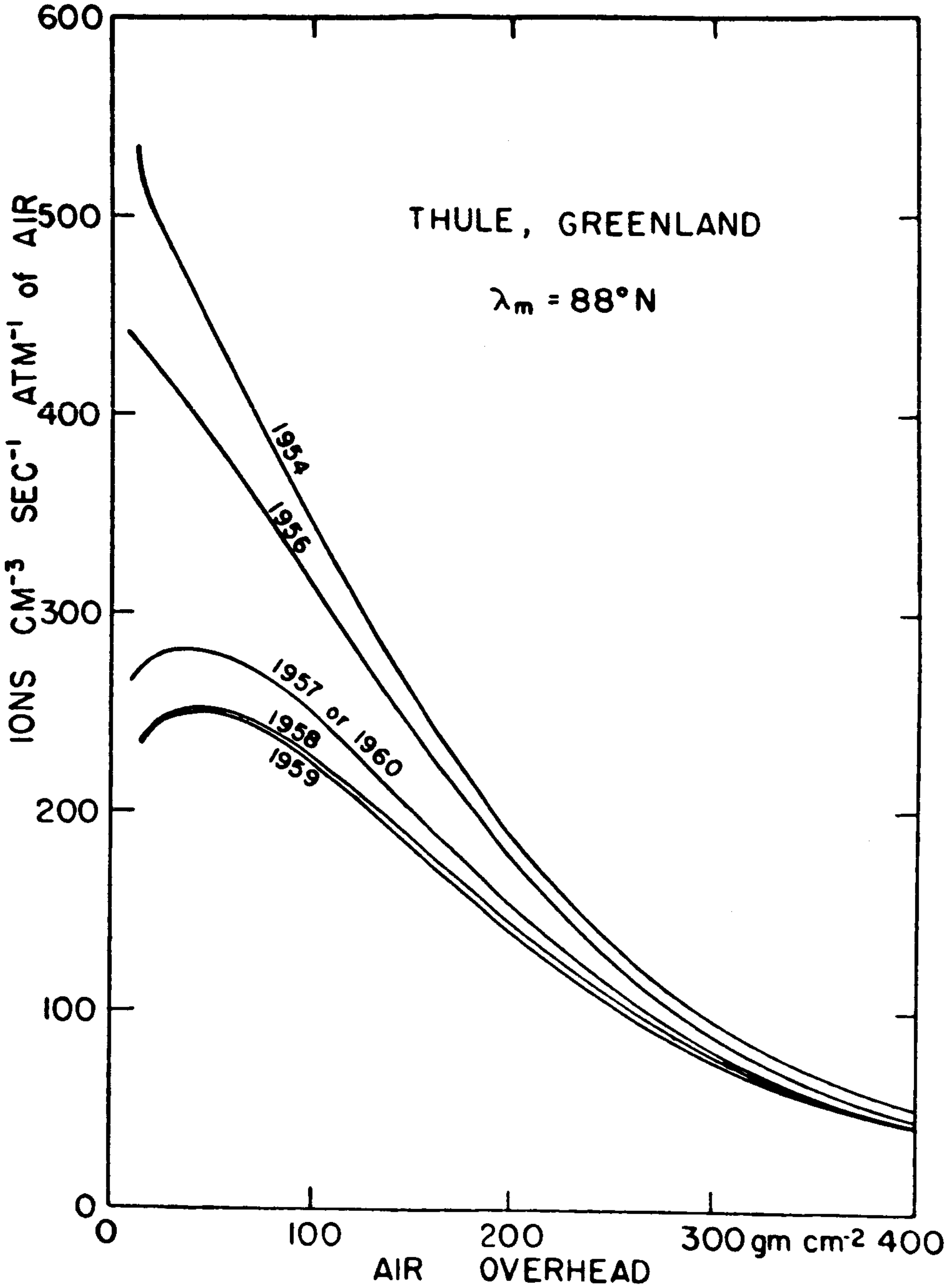
Fig. 9 Counting rate of triple coincidence events on Pioneer V and Explorer VI as a function of the distance from the earth (Fan, Meyer and Simpson, 1960)[14]

Fig. 10 Neutron monitor cosmic ray intensity vs. average sunspot number from 1954 to 1962 (Simpson, 1962)[20]



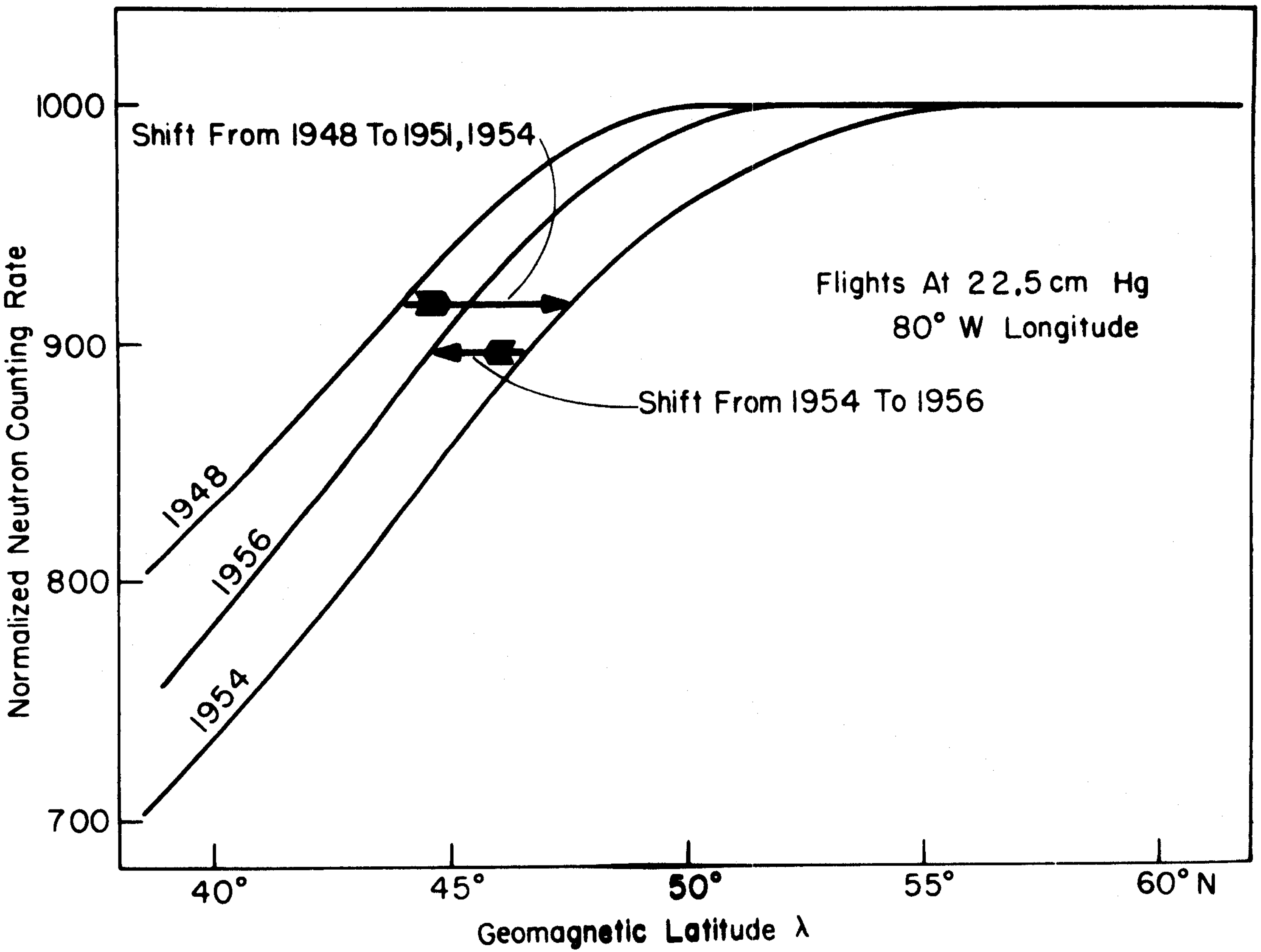
ANNUAL MEANS COSMIC-RAY INTENSITY AT FOUR STATIONS

Fig.1



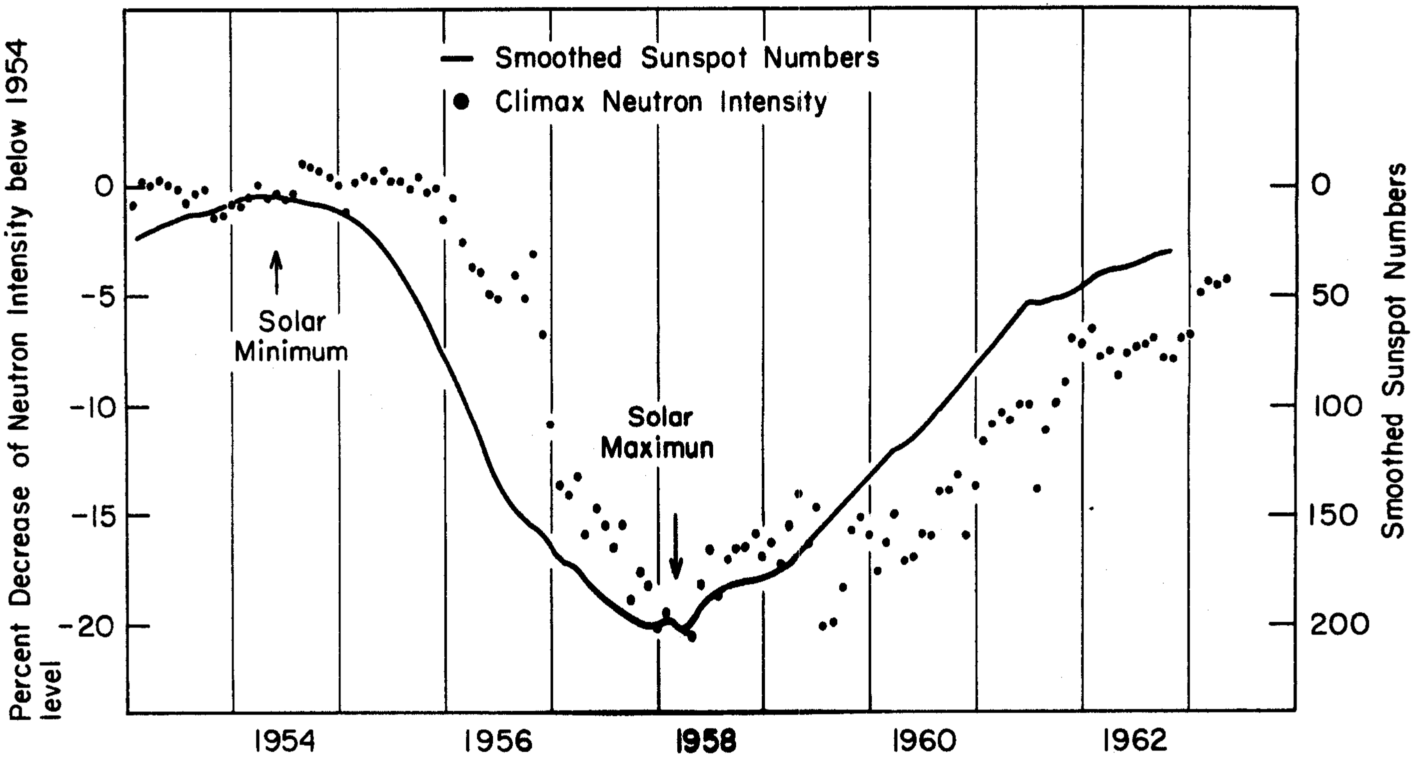
THULE, GREENLAND
$\lambda_m = 88°N$
IONS CM^{-3} SEC^{-1} ATM^{-1} of AIR
AIR OVERHEAD
300 gm cm^{-2}
1954
1956
1957 or 1960
1958
1959
0
100
200
300
400
500
600

Fig.2



1000
900
800
700
Normalized Neutron Counting Rate
Shift From 1948 To 1951, 1954
Shift From 1954 To 1956
Flights At 22.5 cm Hg
80° W Longitude
1948
1956
1954
40°
45°
50°
55°
60° N
Geomagnetic Latitude λ

Fig.3



Smoothed Sunspot Numbers
Climax Neutron Intensity
Solar Minimum
Solar Maximun
Percent Decrease of Neutron Intensity below 1954 level
Smoothed Sunspot Numbers
0
-5
-10
-15
-20
0
50
100
150
200
1954
1956
1958
1960
1962

Fig.4

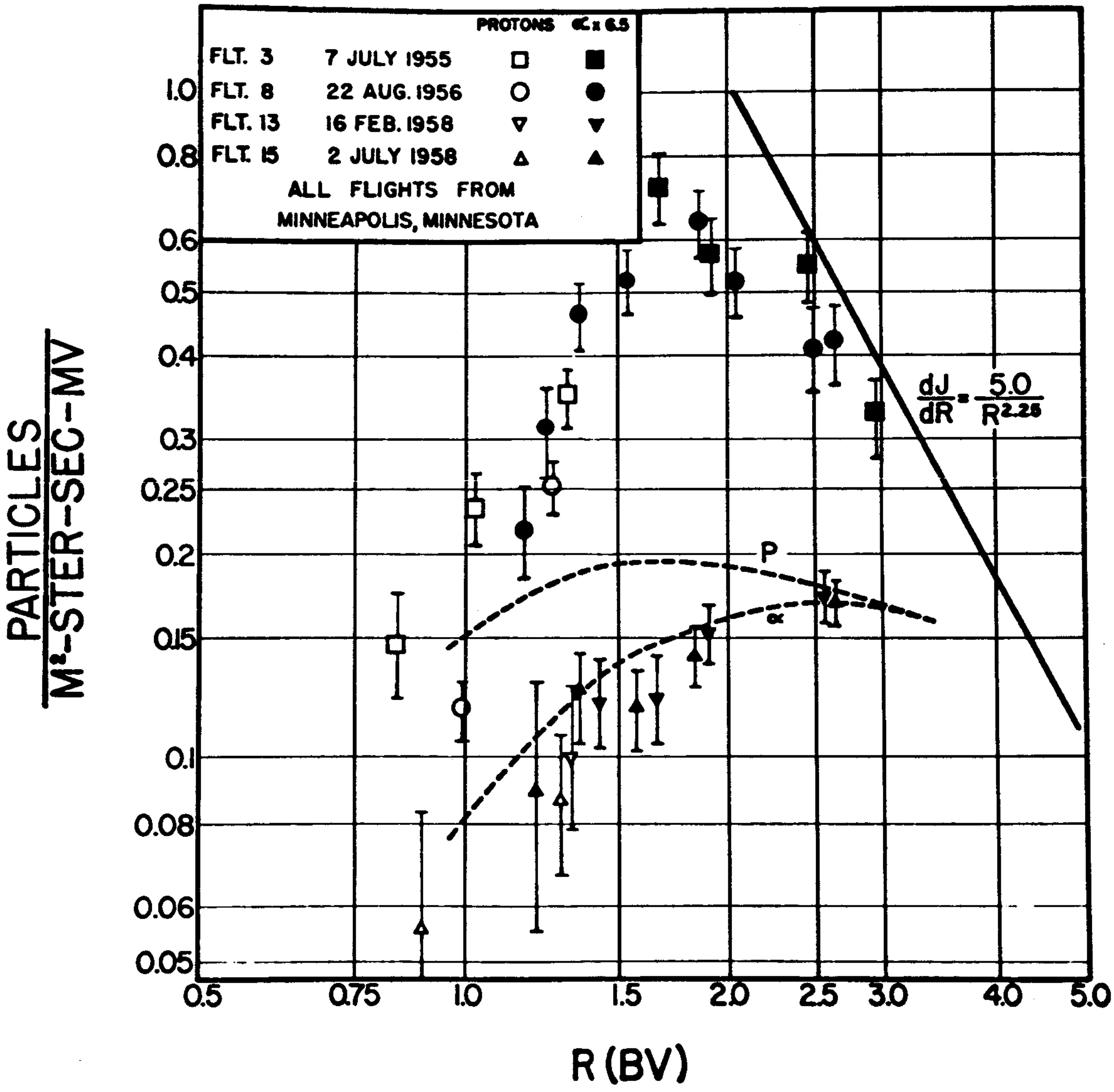
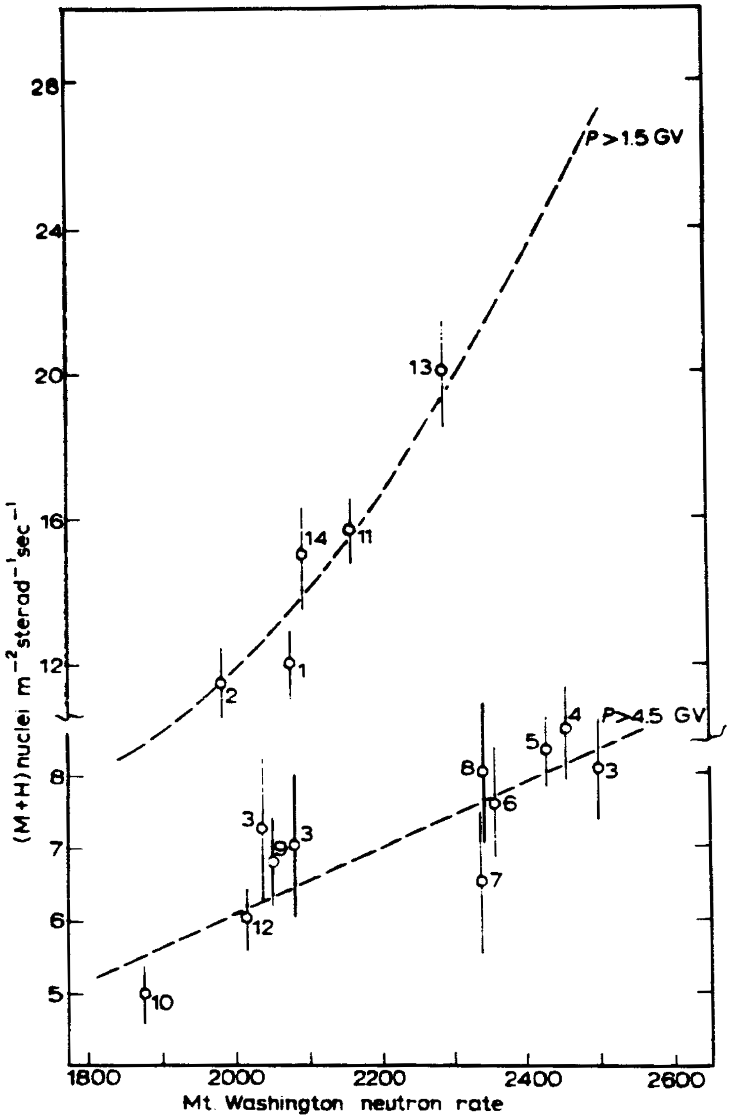

PROTONS
α × 6.5
FLT. 3 7 JULY 1955
FLT. 8 22 AUG. 1956
FLT. 13 16 FEB. 1958
FLT. 15 2 JULY 1958
ALL FLIGHTS FROM MINNEAPOLIS, MINNESOTA
PARTICLES / M²-STER-SEC-MV
$\frac{dJ}{dR} = \frac{5.0}{R^{2.25}}$
P
α
1.0
0.8
0.6
0.5
0.4
0.3
0.25
0.2
0.15
0.1
0.08
0.06
0.05
0.5
0.75
1.0
1.5
2.0
2.5
3.0
4.0
5.0
R (BV)

Fig.5



Integral intensities of (M+H) nuclei.

(1) FICHTEL [1960]
(2) KOSHIBA [1960]
(3) YAGODA [1958]
(4) FOWLER [1956]
(5) APPA RAO [1956], NOON [1957] and ENGLER [1959]
(6) YAGODA [1956]
(7) DANIELSON [1958]
(8) WEBBER [1956]
(9) FREIER [1959]
(10) VAN HEERDEN [1960]
(11) BISWAS [1960a]
(12) GARELLI [1960]
(13) EVANS [1960]
(14) BISWAS [1960b]

Fig.6

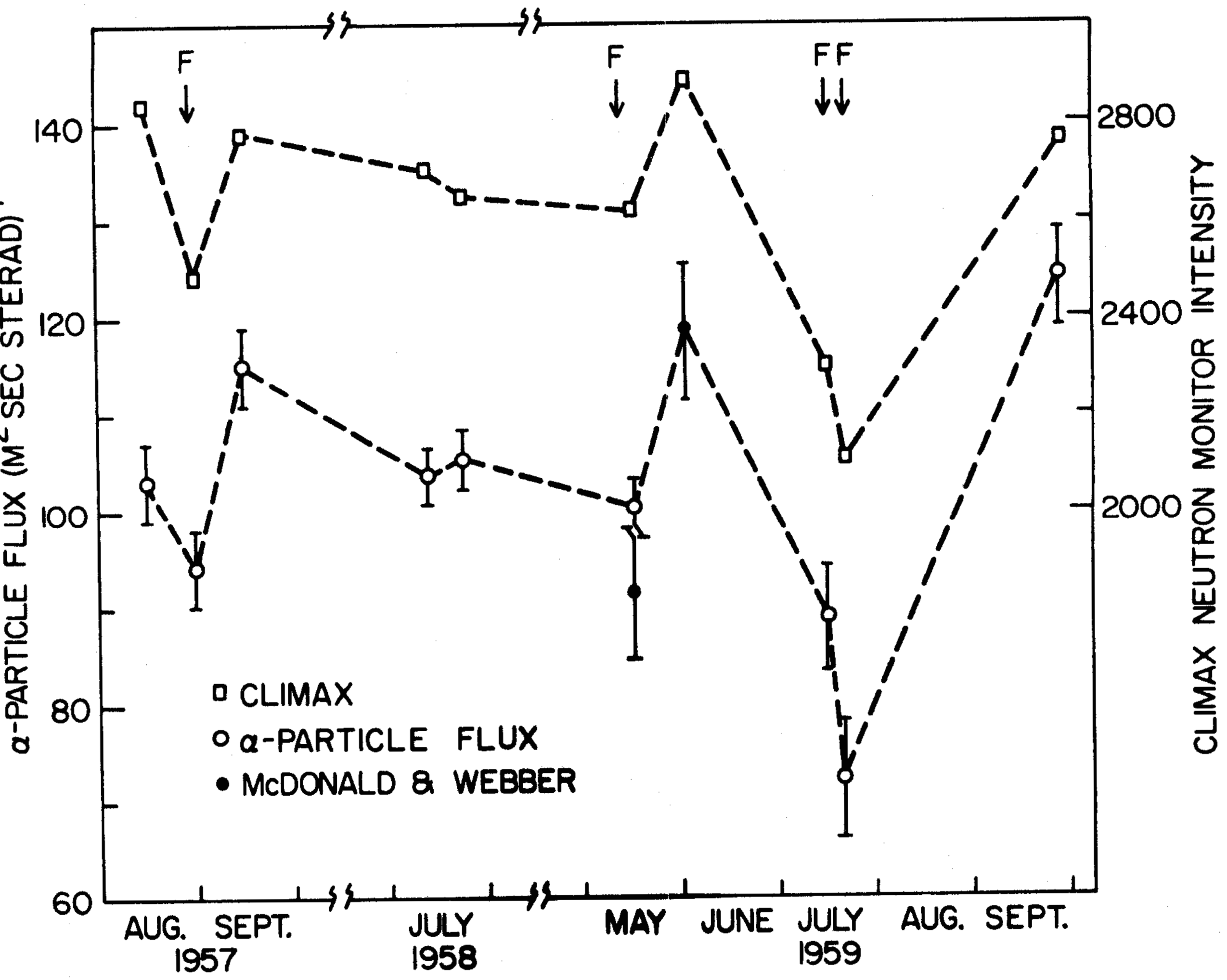
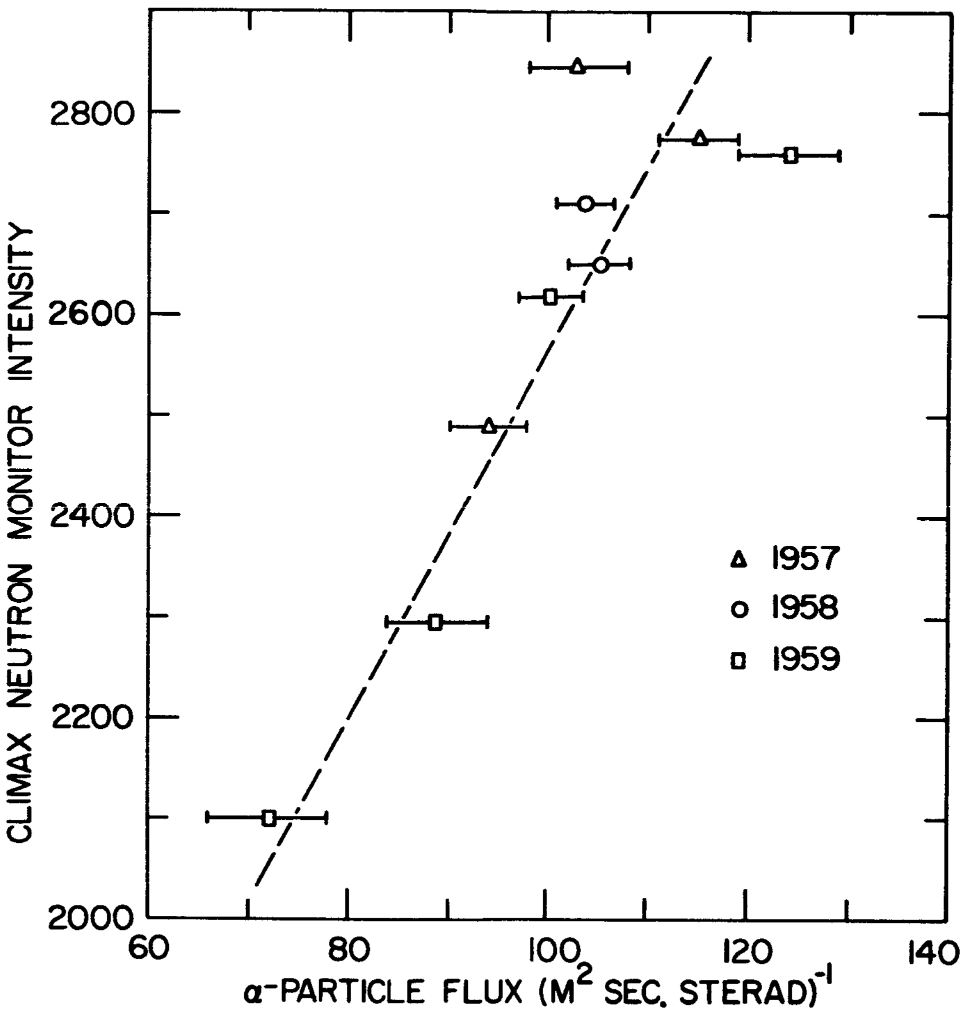

F
F
FF
140
120
100
80
60
2800
2400
2000
α-PARTICLE FLUX (M2 SEC STERAD)-1
CLIMAX NEUTRON MONITOR INTENSITY
CLIMAX
α-PARTICLE FLUX
McDONALD & WEBBER
AUG. SEPT.
1957
JULY
1958
MAY JUNE JULY AUG. SEPT.
1959

Fig.7



CLIMAX NEUTRON MONITOR INTENSITY
2000
2200
2400
2600
2800
60
80
100
120
140
α-PARTICLE FLUX (M² SEC. STERAD)⁻¹
1957
1958
1959

Fig. 8

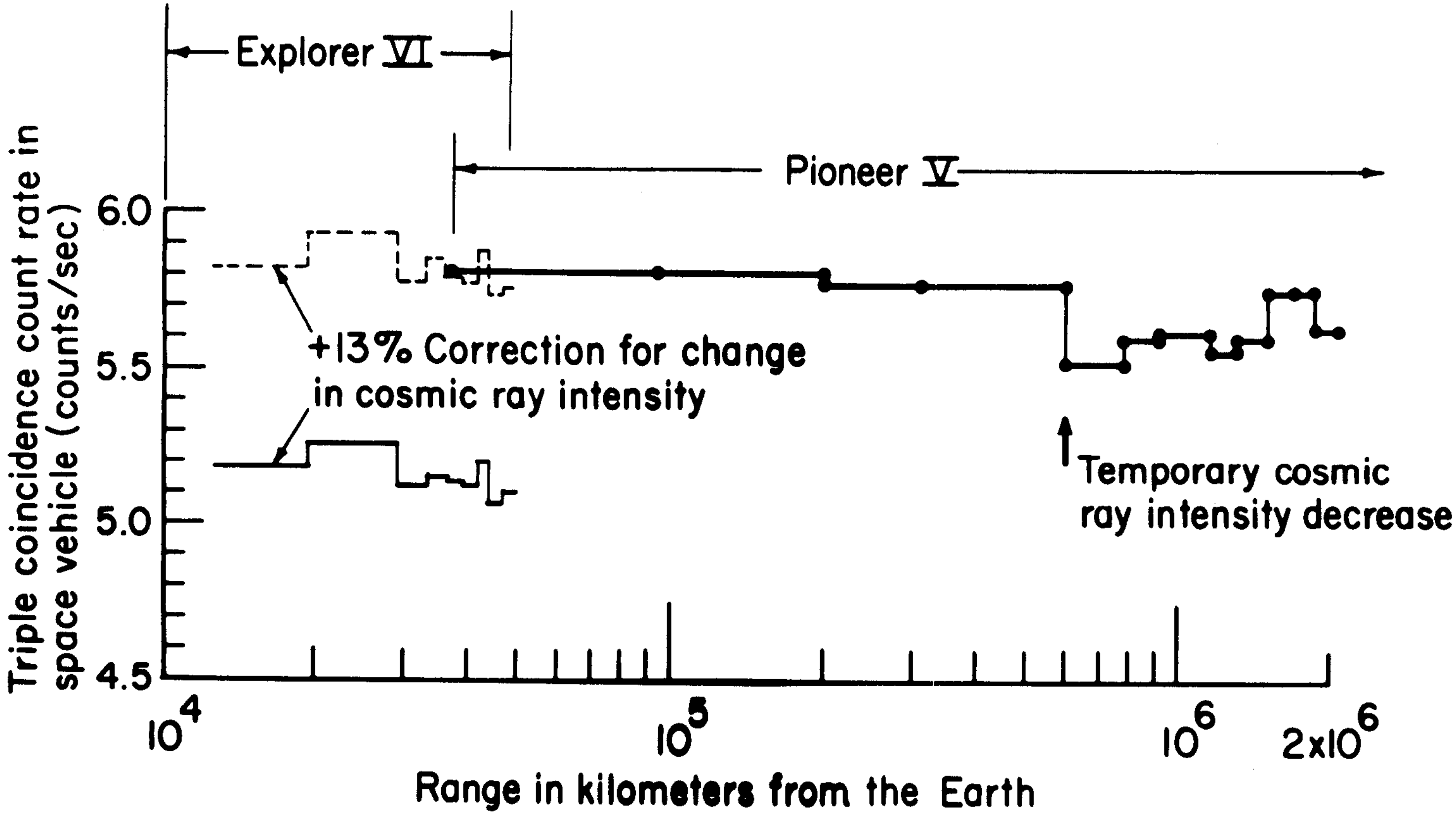
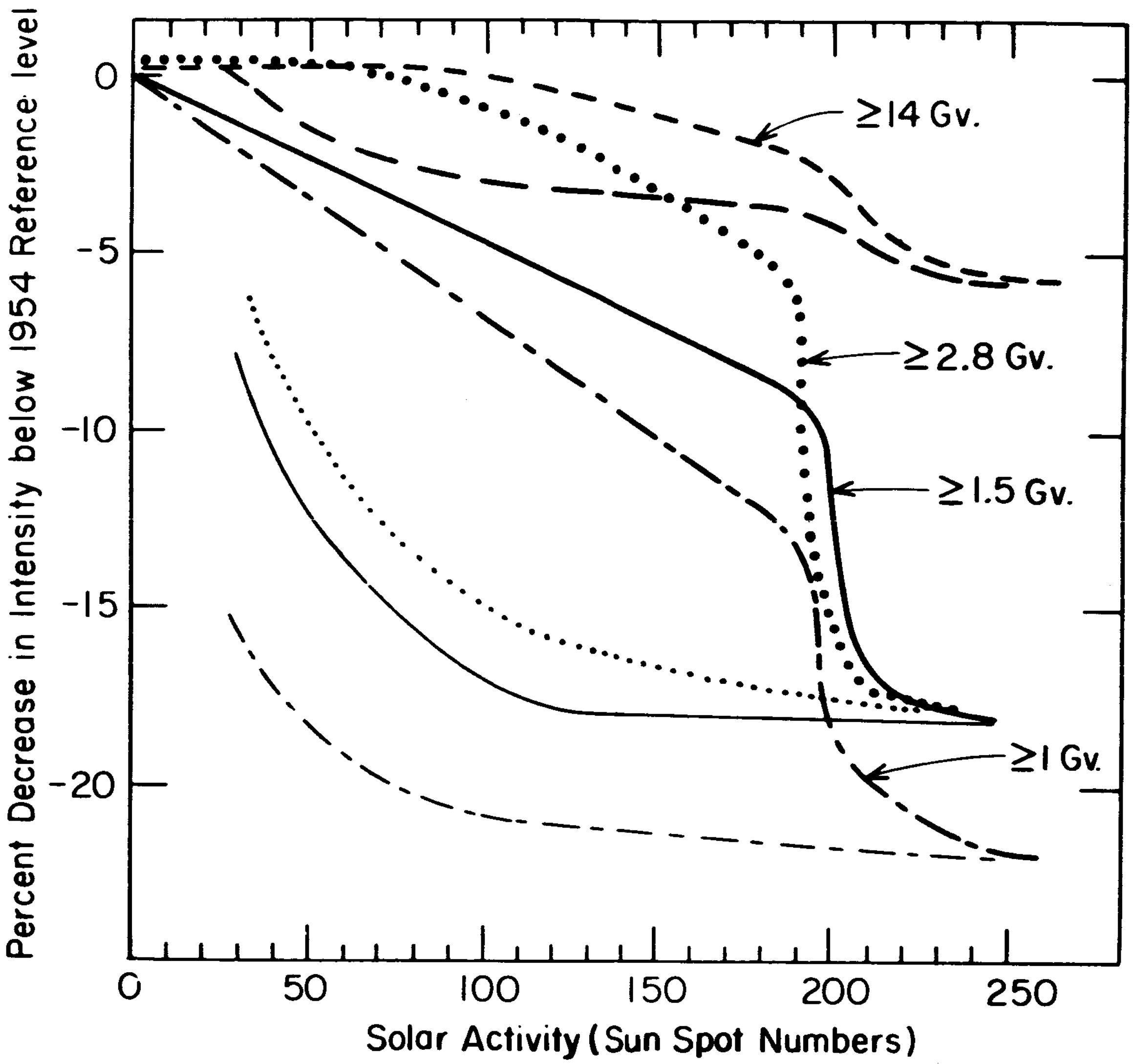

Explorer VI
Pioneer V
Triple coincidence count rate in space vehicle (counts/sec)
6.0
5.5
5.0
4.5
+13% Correction for change in cosmic ray intensity
Temporary cosmic ray intensity decrease
10^4
10^5
10^6
2x10^6
Range in kilometers from the Earth

Fig. 9



Percent Decrease in Intensity below 1954 Reference level
0
-5
-10
-15
-20
0
50
100
150
200
250
Solar Activity (Sun Spot Numbers)
≥14 Gv.
≥2.8 Gv.
≥1.5 Gv.
≥1 Gv.

Fig. 10